A PRELIMINARY ASSESSMENT

OF THE

METRIGUARD 239A

STRESS WAVE TIMER

by

DAVID DUNN

DISSERTATION

School of Forestry

CONTENTS

ABSTRACT

Considerable effort has gone into developing non-destructive testing (NDT) techniques for assessing the performance properties of wood.

This research has established a relationship between certain NDT parameters and the strength characteristics of individual wood members.

To date, NDT techniques have shown the most promise for this type of in-place assessment of wood structures.

This report assesses the validity of non-destructive testing using the Metriguard Model 239A Stress Wave Timer recently purchased by the School of Forestry.

Three pieces of Douglas fir and four pieces of radiata (each 2.0 m x 100 mm x 50 mm) have been used in various experiments to determine the accuracy of the stress wave timer.

The modulus of elasticity of the pieces of timber was calculated and the results were compared to a separate 3-point mechanical bending test carried out on the same timber.

These results showed that on average the stress wave timer (compared to the mechanical test) over-estimated the modulus of elasticity by 17.5%. This difference is considered to be systematic and therefore the stress wave timer appears to be accurate.

Although the stress wave timer accurately indicates the strength properties of wood it remains to be seen if, in its present stage of development, it is of use on a practical basis in the industry.

INTRODUCTION

In August 1992 the School of Forestry purchased the Metriguard Model 239A Stress Wave Timer. This piece of equipment is used for measuring, non-destructively, the strength properties of wood.

Little is known about the function or accuracy of the instrument. **<u>This is a preliminary report designed to give some indication as to the potential usefulness of the stress wave timer</u>.**

The report gives an account of the historical development of non-destructive techniques for measuring timber and reviews the most recent literature on this subject.

The Metriguard Stress Wave Timer measures the strength characteristics of timber by sending a sound wave through the timber and recording the time it takes for that second wave to travel the length of the wood, in microseconds.

This study includes a number of these measurements which have been used to determine whether or not the instrument accurately predicts these strength properties.

SECTION 1 : LITERATURE REVIEW

Historical Development of Non-Destructive Testing Techniques for Wood

---

Non-destructive testing (NDT) techniques for wood products have been developed over the last 30 years. It is an area of increasing importance as the timber industry continues to look for better, non-destructive ways to test their products. More and more this is beginning to apply to the testing of complete wooden structures.

By definition '**non-destructive materials evaluation** is the science of identifying physical and mechanical properties of a piece of material without altering its end-use capabilities' (Ross and Pellerin 1992). This is the key to the procedures - the material being tested is not damaged in any way. The testing procedures provide information on the materials properties, performance or condition.

In the past the NDT techniques have been used in two main ways:

1. Machine Stress Grading (MSR), and
2. Ultrasonic grading of veneer.

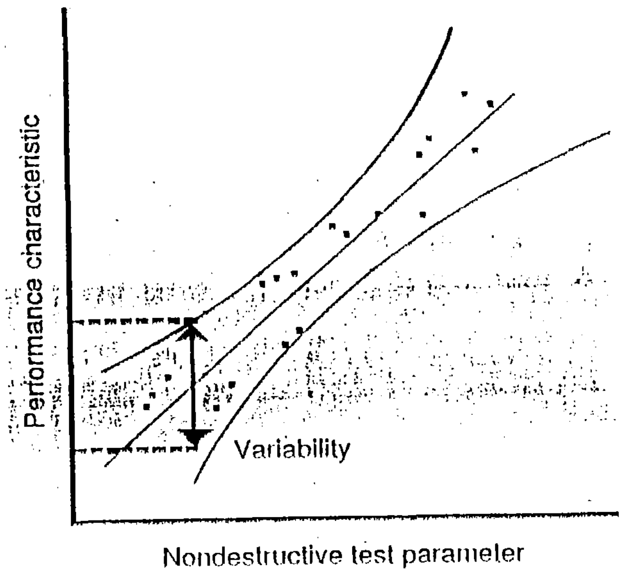
These techniques are used to test separate pieces of material, often in a laboratory or factory situation. There is now an increasing need for complete structures to be tested on site. Today existing structures are more often being repaired or restored and accurate, cost-effective NDT techniques are being developed to help with this. These include static bending techniques, transverse vibration techniques and stress wave techniques. This report is primarily concerned with the stress wave technique.

Materials such as metals and plastics are manufactured and their mechanical properties are known and tightly controlled. Wood, on the other hand, is much more irregular in nature. NDT techniques allow the natural and environmentally induced irregularities in wood to be measured. This information can then be used to accurately identify the mechanical properties of the timber.

Early researchers examined this concept and developed a fundamental hypothesis explaining the relationship between measurable NDT parameters and static mechanical properties.

Jayne (1959) proposed that ' ... the energy storage and dissipation properties of wood materials, which can be measured non-destructively ... are controlled by the same mechanisms that determine the static behaviour of such material' (Ross and Pellerin 1992). Therefore he concluded that statistical regression analysis could be used to establish a mathematical relationship between NDT parameters and performance characteristics (the static elastic and strength behaviour of timber).

The closer the recorded data is grouped about the regression line the more successful an NDT parameter is at predicting performance (see below).



- typical relationship between NDT parameter and performance.

Usually an r-squared value is used to assess the quality of the NDT regressions.

Such studies have led to the development of modern longitudinal stress wave techniques for measuring the performance of timber. The influence that boundary conditions have on the speed of the sound transmission is much less than that for static bending or traverse vibration techniques.

Application of NDT Techniques

There are a number of interesting examples where this stress wave NDT technique has been used to test in-place wood members.

Eighteenth Century Mansion

In 1965 a researcher by the name of Lee was one of the first to use stress wave techniques to evaluate a structure. In this case it was the roof of an 18th century mansion. He estimated the strength loss of purlins by measuring propagation speed of stress waves both parallel and perpendicular to the grain. He then produced a chart relating stress wave velocity and strength.

University Football Stadium

In this example a section of Washington State University's football stadium was tested for safety by a group of engineering consultants and reported sound.

However, when tested informally by some graduate students on an NDT wood course the wooden stadium was found to be very badly decayed. Further tests using stress wave equipment showed that the sound wave propagation time was significantly less in the decayed timber than in solid timber. Once dismantling began the structure collapsed under its own weight.

TRESTLE

This structure was built between 1976 and 1979 and is one of the largest glue-laminated constructions in the world. It is located at Kirtland Air Force Base, New Mexico. TRESTLE is a test stand for aircraft that weigh 250,000 kg. The test platform itself is 61 m x 61 m and is 36 m above the ground.

A few years after construction the Air Force wanted to test aircraft that were much heavier than this, and proceeded to conduct a structural evaluation of TRESTLE. This was done using stress wave techniques. The results showed that the structural frame work was sound and could therefore handle the weight of the heavier aircraft.

These examples show that the stress wave NDT technique for evaluating wooded structures is extremely useful. It is not only accurate but quite simple and inexpensive to carry out. This technique will have an important place in future development of NDT techniques.

Factors Affecting the Application of Stress Wave NDT Grading Techniques

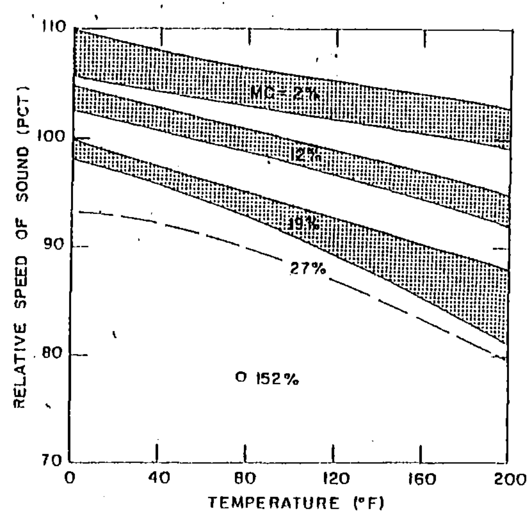
Many factors affect the stress wave transit time in timber. As already mentioned timber is a highly variable material. Much research has been devoted to analysing this variability so that relationships can be drawn between certain characteristics and the stress wave speed along the grain.

Longitudinal stress wave techniques have been used in a number of ways including grading for veneer and laminating stock. However, this has been on a limited basis only. 'A more widespread use of the technique for stress-grading wood products should result from a better understanding of the interaction of stress waves with wood' (Gerhards 1982).

A stress wave will take approximately 50-100 microseconds to travel 30 cm. This is ideal for rapid timber grading. However, factors such as moisture content, temperature and grain angle will affect stress wave speed.

Moisture Content and Temperature

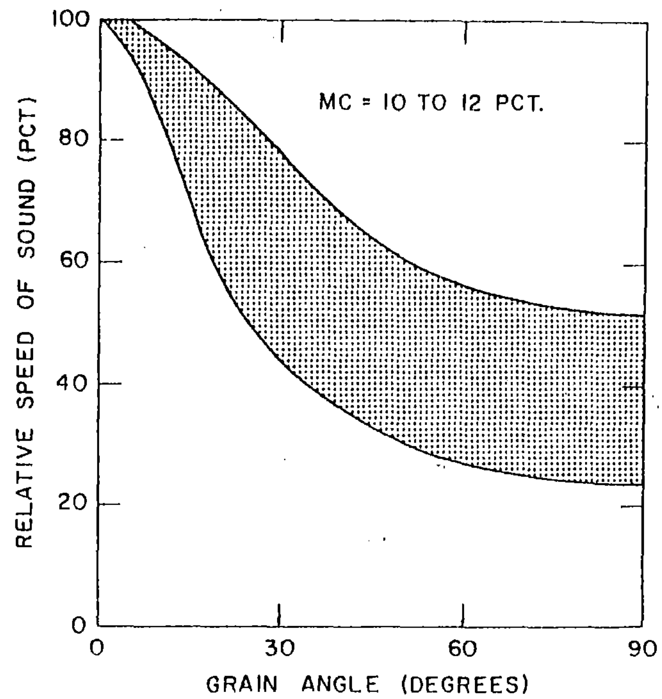
As either moisture content or temperature increases stress wave speed will decrease (see graph below, Gerhards 1982).



- Effect of moisture content and temperature on stress wave speed parallel to grain.

Effect of Grain Angle

Grain angle has a very definite effect on stress-wave speed. As the grain angle increases stress-wave speed decreases. Speed at 90° to the grain is approximately 37% of the speed at zero degrees to the grain (Gerhards 1982). This leads to the important fact that the change in speed is most noticeable at grain angles up to 15° which are commonly associated with lower grades of timber.



- effect of grain angle on stress wave speed.

The effect of cross grain on stress waves in timber is discussed in detail in another paper written by Gerhards (Gerhards 1980).

In this paper Gerhards concludes that ' ... because stress waves travel faster along the grain than across, longitudinal stress waves in wood tend to lead in the direction of the grain slope' (Gerhards 1980). He also concludes that there will be consistent results recorded for stress wave speeds (using different timing methods), only if the stress wave contour remained normal to the direction of transit. Finally he says that the presence of positive or negative cup will have the greatest affect on stress wave speed as timber width increases. The shape of stress wave contours may be affected some distance from the end.

<u>Effect of Knots</u>

The presence of knots and the curved grain around knots reduces stress wave speed. If the piece of timber is fairly wide however, the effect of the knot does not appear to be significant over the total length.

Conclusions from Literature

Based on the research carried out over a long period of time there are two important points which need to be summarised:

1. There is a fundamental relationship between NDT parameters and performance characteristics of wood members.

2. Stress wave NDT techniques have shown the most promise for in-place assessment of wood structures. They are easy to use and relatively low cost.

It is assumed that further research on in-place assessment will concentrate on refining the stress wave NDT technique.

SECTION 2 :

THE METRIGUARD MODEL 239A

STRESS WAVE TIMER

The Metriguard Model 239A Stress Wave Timer (Model 239A) is an instrument used for the non-destructive testing of timber. It can be used to test both individual members or for in-place assessment of wood structures.

The Model 239A does not measure wood properties. It measures the time (in microseconds) that it takes for a stress wave to travel a given distance through the timber being tested. The stress waves induced in the timber move in a uniform way and at a predictable speed as long as the timber is homogeneous throughout the length. Stress waves deviate when passing through a high density or defect area.

This stress wave deviation alters the time it takes the wave to travel the length of the timber. This in turn indicates wood strength, knots, slope of grain, breaks and other timber defects. The instrument can be used on very short lengths and is therefore useful for studying timber characteristics in detail.

Such instruments are also being used in quality control procedures in processing plants as a check against visual stress grading. An example of this is in the manufacture of particleboard. The Model 239A can be used to collect data so that correlations can be made between stress wave time and the performance characteristics of the various products being produced (modulus of elasticity, modulus of rupture and internal bond). This allows quick checks to be made at any point along the production process or even at a warehouse.

Because the Model 239A can measure short time intervals it will allow the manufacturer to locate areas of high or low density, defects or to identify fibre orientation. This will in turn help to increase the homogeneous nature of the timber products.

How the Instrument Works

A diagram and specifications of the 239A has been included as Appendix 1.

The accelerometer is the input device used to detect the passage of the stress wave. The accelerometer generates a charge proportional to the instantaneous acceleration of the body of the device.

In practice this means that the accelerometers are placed against both ends of the timber being tested. There is a start accelerometer and a stop accelerometer. The sensitive axis must be aligned with the direction of the stress wave propagation. As the leading edge of the stress wave passes, the start accelerometer generates a charge signal which is fed to the input amplifier circuit through a cable. When the stress wave reaches the other end the stop accelerometer generates another charge. The stress wave propagation time is then recorded on the liquid crystal display.

The input amplifier gain can be adjusted depending on the sensitivity required. Turning the amplifier gain switches clockwise reduces the level of extraneous noises which will trigger the circuits. It is vital that the circuit triggers at the earliest possible evidence of the stress wave for accuracy.

The impactors are the tools which induce the stress waves into the timber being analysed. In this case two types of impactor were used.

1. <ins>The hammer</ins> which has the start accelerometer built into the head and the stop accelerometer attached to a metal base.

2. <ins>The trombone</ins> which has a pendulum impactor to deliver a repeatable blow every time onto the start accelerometer and a stop accelerometer built onto the instrument. The trombone design measures stress waves over a set distance of 30 cm. It is placed on the flat surface of the timber.

(See Appendix 2.)

The choice of method will depend on the situation. Each method works well. The important point to consider is the need for consistency. The point of impact should be the same each time and at approximately the same strength. Conditions should ideally be quiet and free from vibrations immediately prior to impact. The stop accelerometer, when using the hammer method, should be braced firmly against the end of the timber to ensure that the stress wave is detected at the earliest possible moment.

Stress Waves in Timber

Gerhards (1980 & 1982) discusses how stress waves behave and what affects their travel through timber in a longitudinal direction.

The most important point to note is that only the leading edge of the stress wave affects the stress wave timer measurement. This simplifies what Gerhards (1980) discusses and overlooks the complicated wave structure which wood creates. However, it is important to note that this longitudinal stress wave theory, when applied to wood, assumes two things (Gerhards 1980). First, the stress wave front is normal to the direction of travel, as in a long slender rod. Second, the theory also assumes that wood is homogeneous, which it is not.

It should also be noted that we are talking about both the stress wave and the attendant particle velocity wave which is related to the stress wave by the timber's acoustic impedance (resistance to current). In a travelling wave this means that particle velocity equals stress divided by acoustic impedance. The accelerometers actually detect the particle acceleration. What then is measured by the 239A is the derivative with respect to time of the particle velocity wave and is therefore the derivative of the stress wave except for the acoustic impedance factor.

This is looked at in more detail in the manual which comes with the 239A.

Factors Affecting the Shape of Stress Waves

A more steeply rising measured signal for the stress wave derivative leads to more precise detection time determination. This steeply rising signal is often difficult to obtain.

1. The stress wave must have a fast rising derivative. A good method for achieving this is to impact the timber with a hard moving mass (hammer or pendulum). At the moment of impact the stress wave, having a steep wave front, will be launched. Undesirable softening of the steep wave front can occur in the following ways:

- cushioning by other materials in contact with the timber;
- increasing the size of the impact area as the impactor dents the timber.

2. Attenuation (reduction in force) of the stress wave affects the wave front. Higher frequencies tend to be attenuated more than low frequencies. This results in an undesirable increase in the time it takes for the wave to pass through the timber. This is a result of the non-homogeneous nature of timber.

3. The attachment of the accelerometers to the timber is very important. The accelerometer must be firmly attached to the timber so that a suitable conduit for the passage of the wave is attained. Poor attachment will lead to an increase in propagation time.

Proper attention should be given to all the above in order to keep detection time ambiguity to a minimum.

Gain Adjustments

The 239A allows you to alter the signal amplification received from the accelerometers. The gain should be set as high as possible without having background noise perturb the signal. Indicator dots on the display allow the sensitivity of the start and stop gain to be estimated. False retriggering from subsequent impacts is prevented until the indicator dots go out.

For greatest sensitivity the gain settings on the 239A should be turned to their highest value. Because these instruments are very sensitive, outside noise from machinery or other similar sources can result in false triggering of the detection circuit.

To determine the best gain setting repeated measurements should be made on a piece of timber. Trials should be conducted using different start and stop gain settings to determine which give the best repeatability and make the most sense.

Loose or poorly attached cables or accelerometers will also lead to inaccuracies. Checks should always be made to avoid this.

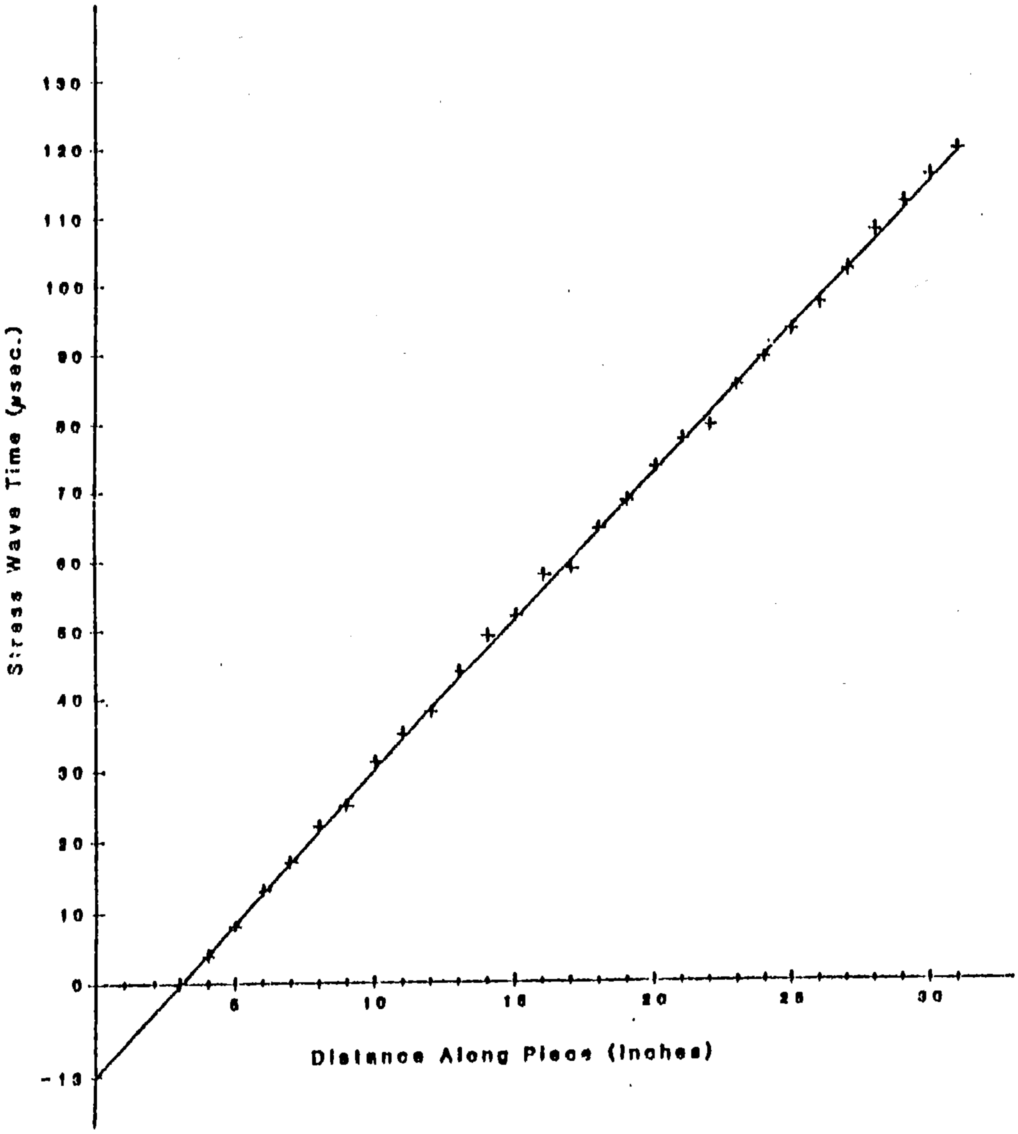
For the 239A to be useful the key is in the preparation. You could not expect to get useable results from an experiment using the 239A unless you have first paid particular attention to the points listed above. It will only be as accurate as you allow it to be. However, as already indicated the 239A has the capacity to be highly accurate and is valuable for a number of purposes. Care must also be taken in the calibration (correction for zero offset) which will be addressed in the following sections of this paper.

Correction for Zero Offset

An understanding of the fundamentals of zero offset correction is important because this paper is primarily concerned with the calibration of the 239A.

Once the best gain settings have been established, stress wave time measurements of a uniform piece of timber can be used to obtain a zero offset time correction value. The correction of data to account for zero offset is particularly important on short lengths of timber. If, for example, a 20.0 cm length of timber had a measured stress wave propagation time of 40 microseconds and a correction time of 10 microseconds, the true value could be out by 25% if the correction time was not taken into account.

Generally, the best method is to collect data at the gain setting decided on, and then to do a linear regression analysis on this data to determine the offset value. The same value could be obtained simply by graphing stress wave time (vertical axis) against distance (horizontal axis) and seeing where the line of best fit intersects the vertical axis. Where the line crosses the vertical axis is the zero offset time. To correct the data the offset time is then subtracted from the measured time. This zero correction fixes the data so that zero distance corresponds to zero time. (See the example below taken from the 239A manual.)



Example of data used to determine zero offset correction value. By subtracting the zero offset value (in this case, -13 microseconds), from each measurement, the best straight line fit to the corrected data will pass through the origin.

SECTION 3 :

CALIBRATION OF THE STRESS WAVE TIMER

Recording of Data

The species selected to calibrate the stress wave timer was Douglas Fir. The timber was imported from North America and is similar to that used for calibration by the manufacturers (Metriguard INC, Pullman, Washington).

Three 2.0 m lengths of 100 x 50 mm clear wood was used for the data collection. For accurate calibration there can be no defects in the timber.

Equipment needed is as follows:

- the Stress Wave Timer;
- a solid bench to set the timer and timber up on;
- paper and pencil to record data;
- metric tape measure;
- accurate scales to weigh timber for density calculations;
- saw to cut timber into sections;
- an environment free from extraneous noise and vibration.

The section previous to this notes several important points regarding the use of the stress wave timer. These should be considered carefully and a full copy of the operating handbook should be obtained and read.

Procedure

Each piece of timber was initially weighed and measured exactly to determine density. The density is required for the modulus of elasticity equation.

Then the stress wave timer was set up with the hammer accelerometer to begin recording the data. All times have been recorded in microseconds. The data has been included as Appendix 3.

Six stress wave times were recorded on each grain setting for each of the three pieces of timber to allow for the calculation of an accurate mean figure.

The first readings were taken on the full 2.0 m (approx) length. Then a 20.0 cm section was cut of the original length and another six readings taken. This procedure was followed until the last 20.0 cm (approx) section had been removed. In the case of piece 1 and gain setting 1 the original length was 207.0 cm and the last was 17.9 cm.

Once the basic data had been recorded the mean figures for each length and gain setting were summarised and recorded in a separate table (see Appendix 4).

This then allowed a simple linear regression to be carried out on the data to provide the offset times used to correct the data for zero offset. The regressions were run for each gain setting.

DATA ANALYSIS AND DISCUSSION OF RESULTS

The results have been summarised on page 16 (Table 1.1 and 1.2) and the corresponding R^2 values have also been noted.

These mean offset time figures are the times, in microseconds, which must be subtracted from raw data to correct the data for zero offset. They have been used in the rest of the figures in this paper.

The R^2 values are all very high and indicate the usefulness of the offset times recorded.

Trombone Experiment

To show the use of the offset data the trombone (239-TC, Appendix 2) was used to record propagation times over 300 mm lengths of the same Douglas Fir pieces. The data for this is included as Appendix 5. Page 17 shows the summary of the results for the trombone experiment.

Table 2.1 shows the three pieces of Douglas fir and the mean times recorded for each setting, 40, 20 and 10. These are all similar as was expected.

Table 2.2 shows how the data is adjusted for offset using the previously calculated offset times.

The adjusted figure is then compared to the estimated figure in Table 2.3 and the difference between the two is shown).

<u>The estimated value is calculated as follows</u>.

Example of the estimate calculation for piece 1 and a gain setting of 40.

From the original regressions summarised in Appendix 4 the equation for piece 1 gain 40 is

$$Y = 1.758X + 6.4$$

The constant is ignored and the following equation is solved

$$dy/dx = 1.758$$

$$dy = 1.758 \times dx$$

where dx = 30 cm

and dy = time

(30 cm is the distance between the trombone accelerometers)

therefore dy = 52.74 microseconds.

The results of Table 2.3 show that there is almost no difference between estimated times and the times recorded using the stress wave timer.

This is for the three gain settings indicated only. The lower gain settings tended to give much more erratic readings and therefore these were not used for the bulk of the study.

Further to this, Figure 1 gives an indication as to the type of relationship one might expect between distance and time. The graph shows that as you increase the distance between the accelerometers in regular amounts you get an equally regular increase in propagation times. In other words, it takes a longer time for a stress wave to pass through a long piece of timber than a short piece, which is to be expected.

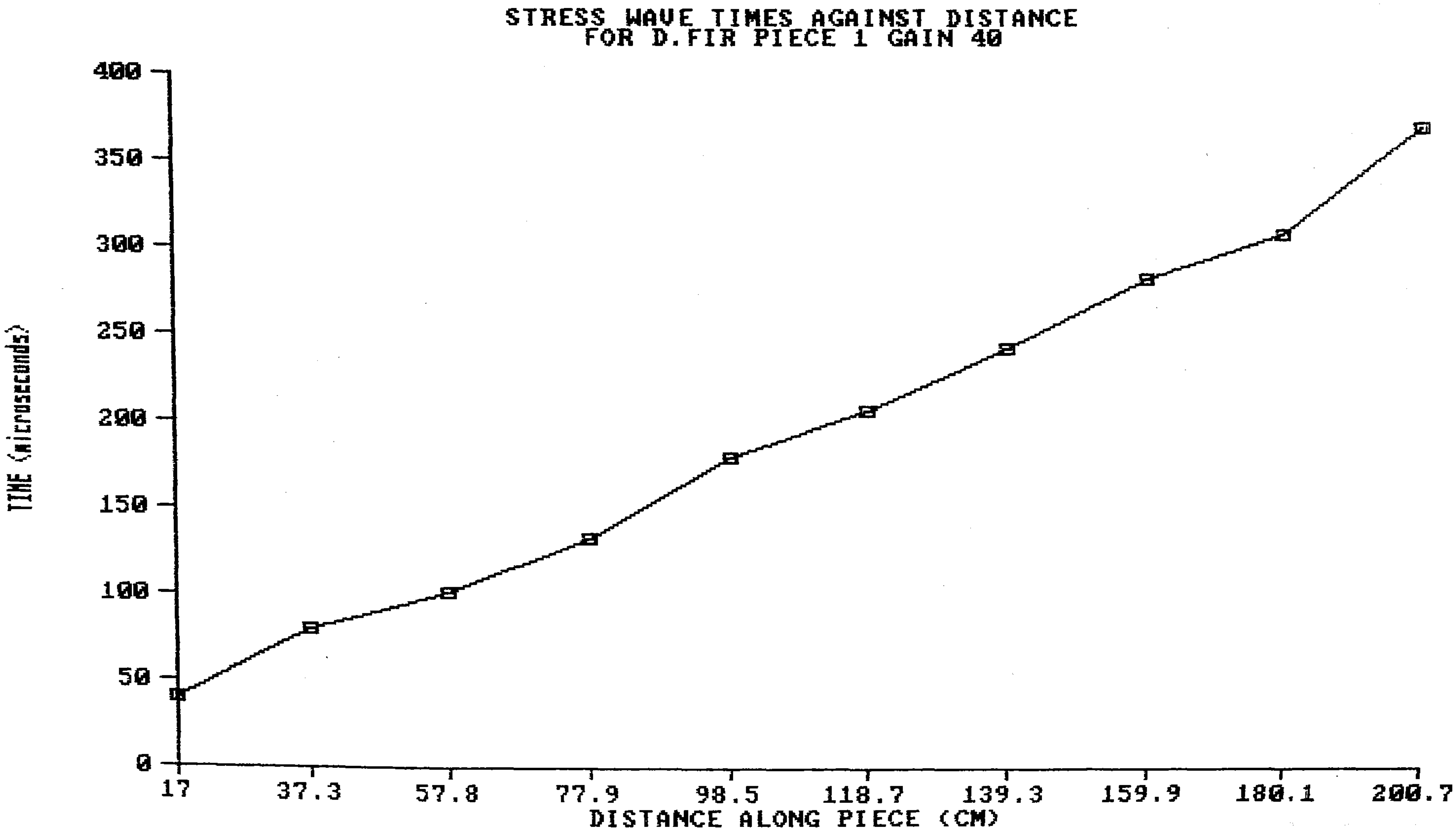

STRESS WAVE TIMES AGAINST DISTANCE
FOR D.FIR PIECE 1 GAIN 40
TIME (microseconds)
400
350
300
250
200
150
100
50
0
17
37.3
57.8
77.9
98.5
118.7
139.3
159.9
180.1
200.7
DISTANCE ALONG PIECE (CM)

Table 1.1: Summary of Offset Times for Douglas Fir

Gain	Piece			Means
	One	*Two*	*Three*	
40	6.4	6.3	6.1	6.3
20	4.8	5.4	6.9	5.7
10	3.5	6.5	4.4	4.8
4	3.0	4.3	1.0	2.8
2	1.3	- 2.5	3.3	0.7
1	- 3.1	- 5.0	- 4.7	- 4.3

Table 1.2: R^2 Values for Pieces 1 - 3

Gain	Piece			Means
	One	*Two*	*Three*	
40	0.998	0.994	0.991	0.994
20	0.998	0.992	0.992	0.994
10	0.998	0.992	0.988	0.993
4	0.997	0.992	0.984	0.991
2	0.996	0.992	0.979	0.989
1	0.994	0.985	0.970	0.983
			R^2 mean	0.991

The offset figures are taken from the 'constant' value calculated by the regression outputs included in Appendix 2.

The R^2 values are from the same output information.

Table 2.1: Average Trombone Data Gain 10 - 40
Douglas fir - pieces 1 - 3

Gain	Piece 1	Piece 2	Piece 3
40	57.0	55.8	59.3
20	58.0	56.2	60.3
10	59.5	57.8	61.4

Table 2.2: Trombone Data Adjusted for Offset

Gain	Piece 1			Piece 2			Piece 3		
	40	*20*	*10*	*40*	*20*	*10*	*40*	*20*	*10*
Mean	57.0	58.0	59.5	55.8	56.2	57.8	59.3	60.3	61.4
Offset	- 6.4	- 4.8	- 3.5	- 6.3	- 5.4	- 6.5	- 6.1	- 5.7	- 4.8
Adjust	50.6	53.2	56.0	49.5	50.8	51.3	53.2	54.6	56.5

Table 2.3: Estimated Transit Time for Sound Wave to Travel Along
a 300 mm Section

Gain	Piece 1			Piece 2			Piece 3		
	40	*20*	*10*	*40*	*20*	*10*	*40*	*20*	*10*
Adjust	50.6	53.2	56.0	49.5	50.8	51.3	53.2	54.6	56.6
Est	52.7	52.9	53.4	51.9	51.8	51.7	52.0	51.9	52.8
Diff	2.1	- 0.3	- 2.6	2.4	1.0	0.4	- 1.2	- 2.7	- 3.8

SECTION 4 :

CALCULATION OF MODULUS OF ELASTICITY

To further validate the results that the model 239A has given us we need also to look at the difference between the Modulus of Elasticity (MOE) as calculated by:

1. A standard mechanical 3-point bending test, and
2. An estimate calculated mathematically using an equation and a stress wave time.

The results of this comparison are summarised on page ? Table 3.1. The test was carried out on each of the original seven pieces of timber as indicated.

The key figures to note are in the right hand columns of Table 3.1. The average MOE is the mean of the four MOE readings in the two columns to the left of this, headed joist MOE and plank MOE.

The joist and plank MOE figures were calculated by Purwoko (a postgraduate student) using the following formula,

$$\text{MOE} = \frac{(P1 - P2)\,L^3}{4.6g\;bd^3y}$$

P1 = initial load

P2 = final load

L = span

b = width

d = depth

y = deflection

The estimated MOE figures as recorded in Table 4.1 were calculated using recorded stress wave times and the following formula,

$$E = V^2 \times d \times 1/g$$

where

$$V = \text{velocity} = \frac{\text{distance accelerometers (m)}}{\text{propagation time (sec)}}$$

$$d = \text{density} = \frac{\text{weight (kg)}}{\text{volume } (m^3)}$$

$$g = \text{acceleration due to gravity.} = 9.804\ s^2/m$$

The units for MOE (E above) are kg/m^3 (pascals).

Example,

$$V = \left(\frac{207}{369.7 \times 10^{-6}} \right)^2$$

$$d = 643\ kg/m^3$$

$$1/g = 1/9.804$$

if $E = V^2 \times d/g$

then $E = 20.6$ Gpa

Thus Table 4.1 gives the summary of all MOE figures calculated mechanically and mathematically and indicates the percentage difference between the two calculations.

The difference is shown to be small and the mean difference is 17.5%. This means that the stress wave timer, on average, will over-estimate the MOE by 17.5%.

Figure 2 is a graph of the regression comparison between the machine bending test and the stress wave timber test for calculating MOE. It indicates a very close relationship between the two. The r^2 value is 0.81.

This suggests that the model 239A does a very good job of estimating MOE for timber. There is no indication of any significant problems with consistency as far as recordings are concerned as long as the correct procedures are followed.

The first row of data for each timber was obtained by testing as a joist then as a plank. The second row was obtained using a similar procedure but in different edges/faces.

For example, number 1111 indicates that the first face of the timber was placed in tension when testing as a joist, then the second face was placed in tension when testing as a plank. Data 1121 indicates the third face was in tension when testing as a joist and the fourth face in tension when testing as a plank.

Table 3.1: Results for Bending Test of Seven Timbers to Calculate Modulus of Elasticity.

The three point loading test was carried out by Purwoko. Tested as a joist. Tested as a plank.

ID Num	Int Load (kN)	Fin Load (kN)	Def2 (mm)	Def2 (mm)	Int Load (kN)	Fin Load (kN)	Def1 (mm)	Def2 (mm)	Joist MOE (GPa)	Plank MOE (GPa)	Avg MOE (GPa)
1111	1.12	3.19	1.94	1.83	0.47	1.28	2.53	2.55	16.81	18.55	
1121	1.12	3.17	1.70	1.59	0.43	1.26	2.62	2.51	19.09	18.82	18.3
2111	1.14	3.13	1.46	1.64	0.47	1.28	2.24	2.27	19.66	20.89	
2121	1.08	3.13	1.51	1.64	0.47	1.28	2.43	2.22	19.93	20.26	20.2
3111	1.19	3.11	1.65	1.59	0.38	1.28	2.62	2.65	18.15	19.86	
3121	1.10	3.24	1.80	1.83	0.45	1.28	2.53	2.55	18.05	19.00	18.8
4111	1.06	3.09	6.56	5.83	0.43	1.24	9.62	9.74	5.02	4.87	
4121	1.07	3.09	6.22	6.17	0.41	1.24	8.07	7.95	4.99	6.03	5.2
5111	1.10	3.10	3.35	2.80	0.44	1.24	4.08	3.86	9.96	11.72	
5121	1.08	3.09	3.45	2.94	0.43	1.26	4.37	4.29	9.63	11.16	10.6
6111	1.07	3.07	5.64	5.35	0.44	1.24	7.34	6.70	5.57	6.63	
6121	1.03	3.11	6.27	5.64	0.43	1.25	8.12	7.90	5.35	5.95	5.9
7111	1.08	3.11	3.16	3.23	0.45	1.23	4.08	4.43	9.72	10.66	
7121	1.12	3.18	3.26	3.13	0.45	1.24	4.52	4.24	9.87	10.48	10.2

Note: 1-3 = Douglas Fir Clears
4-7 = Radiata

Each timber was tested four times, twice as a joist and twice as a plank.

All Modulus of Elasticity figures were higher when tested as a plank than as a joist.

The formula used to correct data for shear modulus has been included in the text.

Table 4.1: Comparison of Machine Bending Test and Stress Wave Timer Test for Modulus of Elasticity

SPECIES	TEST (MOE - GPa) Corrected		
	Machine	S/W Timer	% Difference
D. Fir 1	18.3	20.6	11.0
D. Fir 2	20.2	21.0	3.9
D. Fir 3	18.8	20.8	9.6
Radiata 4	5.2	6.5	20.0
Radiata 5	10.6	19.6	46.0
Radiata 6	5.9	6.3	6.8
Radiata 7	10.2	13.6	24.9
			17.5

(Machine figures corrected for shear modulus.)
(Stress wave figures corrected for offset.)

Therefore the stress wave timer is shown to over estimate MOE by approximately 17.5%.

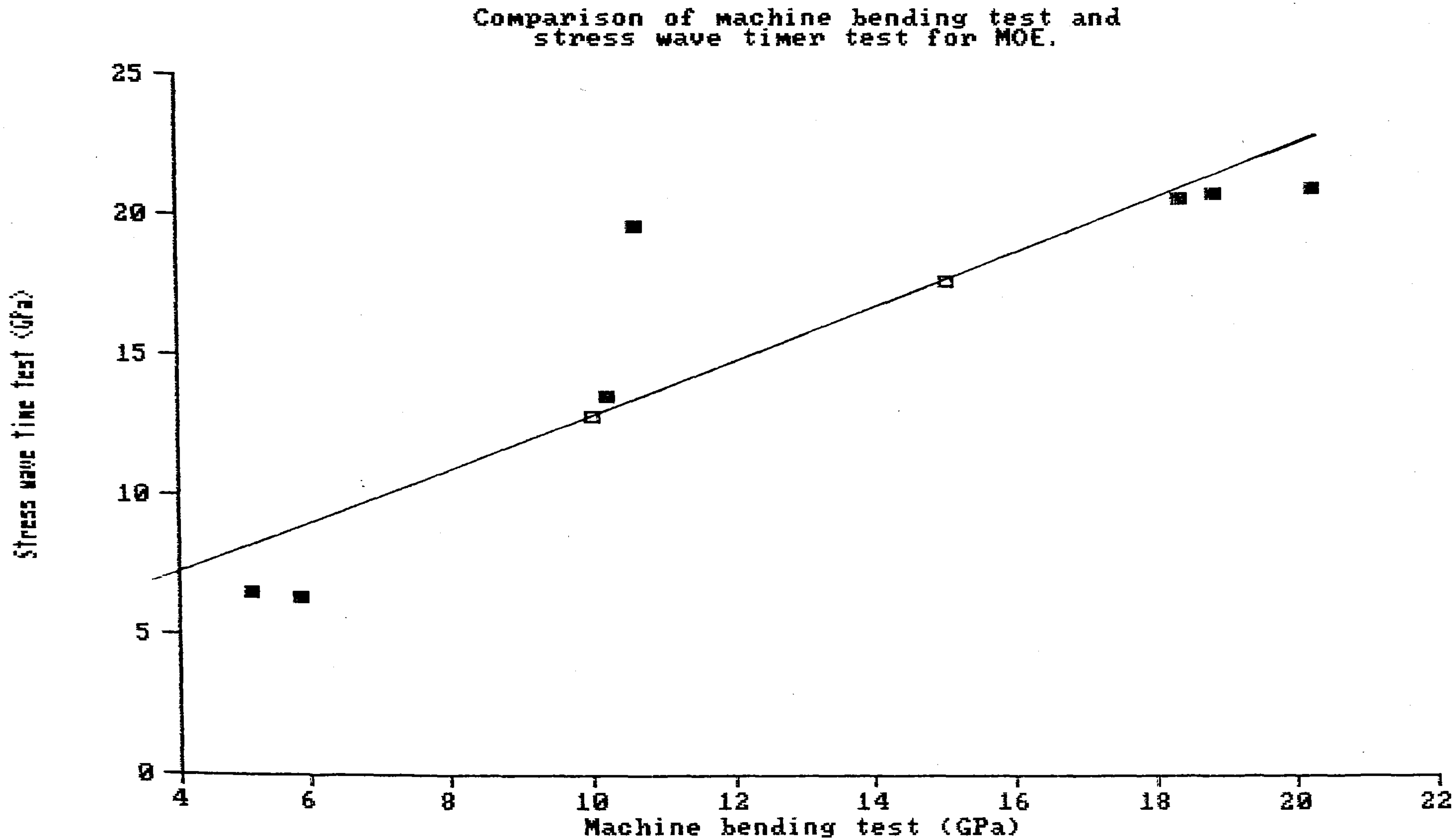
Regression Analysis of Machine Bending Test and Stress Wave Timer Test

(For D. Fir & Radiata, 7 pieces)

Regression Output:

Constant	3.277948
Std Err of Y Est	3.210515
R^2	0.809180
No of Observations	7
Degrees of Freedom	5
X Coefficient	0.958344
Std Err of Coefficient	0.208125

Equation: $Y = 0.958X + 3.28$


Comparison of machine bending test and
stress wave timer test for MOE.
Stress wave time test (GPa)
Machine bending test (GPa)
0
5
10
15
20
25
4
6
8
10
12
14
16
18
20
22

SECTION 5 :

ESTIMATION OF WOOD CHARACTERISTICS USING THE STRESS WAVE TIMER

This experiment took four pieces of 100 x 50 mm radiata which had been cut into 20 cm lengths and measured the propagation times for each piece.

The data base for this particular experiment is much less than originally intended. The pieces were left unattended for several weeks and a number went missing. However there were enough remaining to allow the experiment to continue and for some results to be shown.

The four pieces of radiata can be described as follows:

1. Clear radiata with pith;
2. Knotty radiata with pith;
3. Clear radiata with no pith;
4. Knotty radiata with no pith.

The recording of the stress wave times for this experiment was carried out in an identical manner to the previous experiments. The actual measurements are recorded in Appendix Six. The summary and discussion of the results are on Page 37.

It is clear from this that the natural variability of timber affects the time it takes for a sound wave to pass through the timber. We have shown that the 239A accurately measures this propagation time. We can therefore conclude that the 239A has the potential to greatly reduce the time taken and the cost associated with in-place testing of wood members. The practical benefits of this have already been discussed.

Radiata itself has the potential to be highly variable in its nature. Defects such as knots, spiral grain and variable density appear to have the greatest affect.

Summary of Stress Wave and Density Data for the 4 Types of Radiata

Type 1 = Clear radiata with pith
Type 2 = Knotty radiata with pith
Type 3 = Clear radiata with no pith
Type 4 = Knotty radiata with no pith

	Type 1	**Type 2**	**Type 3**	**Type 4**
Mean Time	59.2	64.9	50.0	64.8
Offset	- 6.3	- 6.3	- 6.3	- 6.3
Corrected	52.9	58.6	43.7	58.5
Density kg/m^3	418.2	506.0	510.9	529.0

Discussion of Results

Type 1 and 3 have shorter propagation times than those recorded for Type 2 and 4 radiata.

This is due to the fact that they are clear samples cut more or less parallel to the grain. There also did not appear to be any other grain defects present.

These characteristics allow the stress waves to pass uninterrupted down the length of the sample, hence, the shorter times recorded.

It is also important to note that Type 1 and 3 tend to be in the lower density range which will also contribute to the shorter propagation times recorded.

Type 2 and 4 have longer propagation times than those recorded for Type 1 and 3.

These samples are not clear and contain knots and grain distortions. Grain distortions are greatest around the knots. The grain angle is also less uniform than in the clear samples.

Stress waves are slowed down as they move through or around these defects.

These samples are in the higher density range due to the presence of knots. Type 4 has no pith and this will explain the fact that it has the highest density recorded.

RING WIDTH AND DISTANCE FROM PITH

The next experiment deals with how propagation time alters in response to changes in density, mean ring width and mean distance from the pith of the original stem. The same pieces of radiata were used as in the previous experiment.

The collected data is recorded in Appendix Seven. Page 41 has the summary of Types 1 and 3 radiata. Only these two types had enough pieces left to make up a suitably large data base. Both types were clear radiata and therefore the propagation times would not be different. The two types are therefore considered to be the same.

Linear regressions were run comparing density, ring width and ring distance from the pith with propagation times. These results are shown on page 44. Graphs of these relationships are on pages 45-47. The stress wave times are all for 20 cm lengths of timber.

Discussion of Results

Density and Stress Wave Time

With an r^2 value of 0.28 density did not appear to show a particularly close relationship to stress wave time. However even though the r^2 is low the graph (page 45) does indicate the expected trend. As density increases the time it takes for the stress wave to pass through the wood decreases. With wood cells packed closely together in dense wood the stress wave passes more easily along the length.

Ring Width and Stress Wave Time

This relationship had better accuracy, and r^2 of 0.39. These results again show the expected trend. Narrow ring widths in radiata are associated with higher density wood. On page 46 the graph shows that as ring width decreases the time it takes for the stress wave to pass along the wood also decreases.

Distance from Pith and Stress Wave Time

This regression gave an r^2 of 0.36. The graph (page 47) indicates that as you move towards the outside of the stem, away from the pith, the stress wave takes less time to travel the length of the wood. As this is clear radiata there will be no major defects in the outer wood to slow down the propagation times. The nature of the pith of radiata is such that this is where large defects occur. The 239A stress wave timer has proven to be sensitive to these defects.

Density may also be higher and more uniform the further you move away from the pith. This will depend on individual pieces of timber. Wood will differ in its properties depending on factors such as climate, location and wind. For example, radiata grown in Southland has a lower density than that grown in Northland. Canterbury radiata tends to have a high incidence of resin pockets due to wind.

Because the results indicate the expected trends it is probable that more accurate results could be achieved by increasing the data base.

MULTIPLE REGRESSION ANALYSIS

To further validate these results multiple regressions were run to compare two variables against stress wave time. The regressions were:

1. Stress Wave Time against Density and Ring Width;
2. Stress Wave Time against Density and Distance from Pith.

These results are shown on page 46.

Discussion of Results

The results from the multiple regression analysis were similar to the regressions with only one x-variable.

For density and ring width the r^2 value is 0.40 and for density and distance from pith it is 0.36.

Increasing the number of variables in the regression analysis has therefore not increased the accuracy of the results.

Regression Analysis of Type 1 and 3 Radiata.
Stress Wave Time Against Density, Ring Width and Distance of Wood from Pith

	CORRECTED DATA FOR CLEAR RADIATA				
	Mean Stress Wave Times (Microseconds)		*Mean Densities (kg/m^3)*	*Ring Width (cm)*	*Distance from Pith (cm)*
A	44.7		547	0.8	15.0
B	47.7		562	0.8	15.3
C	55.3		555	0.9	13.0
D	49.7		569	0.8	13.3
E	50.0		538	0.8	12.7
F	49.7		569	0.9	12.5
G	44.7		544	0.9	15.3
H	53.0		569	0.8	14.5
I	48.5		545	0.8	14.5
J	45.7	Type 3	554	0.8	14.3
K	59.0		418	1.3	5.3
L	40.2		559	0.8	11.5
M	49.8		560	0.9	12.4
N	45.3		554	0.9	14.5
O	51.1		390	1.5	4.6
P	56.6		382	1.3	5.5
Q	53.8		383	1.3	5.0
R	55.8		398	1.3	5.7
A	55.0		390	1.3	6.0
B	58.0		438	1.3	5.3
C	47.5	Type 1	396	1.3	5.0
D	56.0		501	1.3	4.6
E	50.2		398	1.3	5.1
F	50.7		386	1.2	3.4
Mean =	50.8		488	1.1	9.8

REGRESSION RESULTS

DENSITY (kg/m^3)

Regression Output:

Constant	66.36571
Std Err of Y Est	4.161902
R^2	0.280698
No of Observations	24
Degrees of Freedom	22
X Coefficient(s)	-0.03201
Std Err of Coefficient	0.010927

$$Y = -0.32X + 66.37$$

RING WIDTH (cm)

Regression Output:

Constant	38.01714
Std Err of Y Est	3.847025
R^2	0.385421
No of Observations	24
Degrees of Freedom	22
X Coefficient(s)	12.07859
Std Err of Coefficient	3.251814

$$Y = 12.08X + 38.02$$

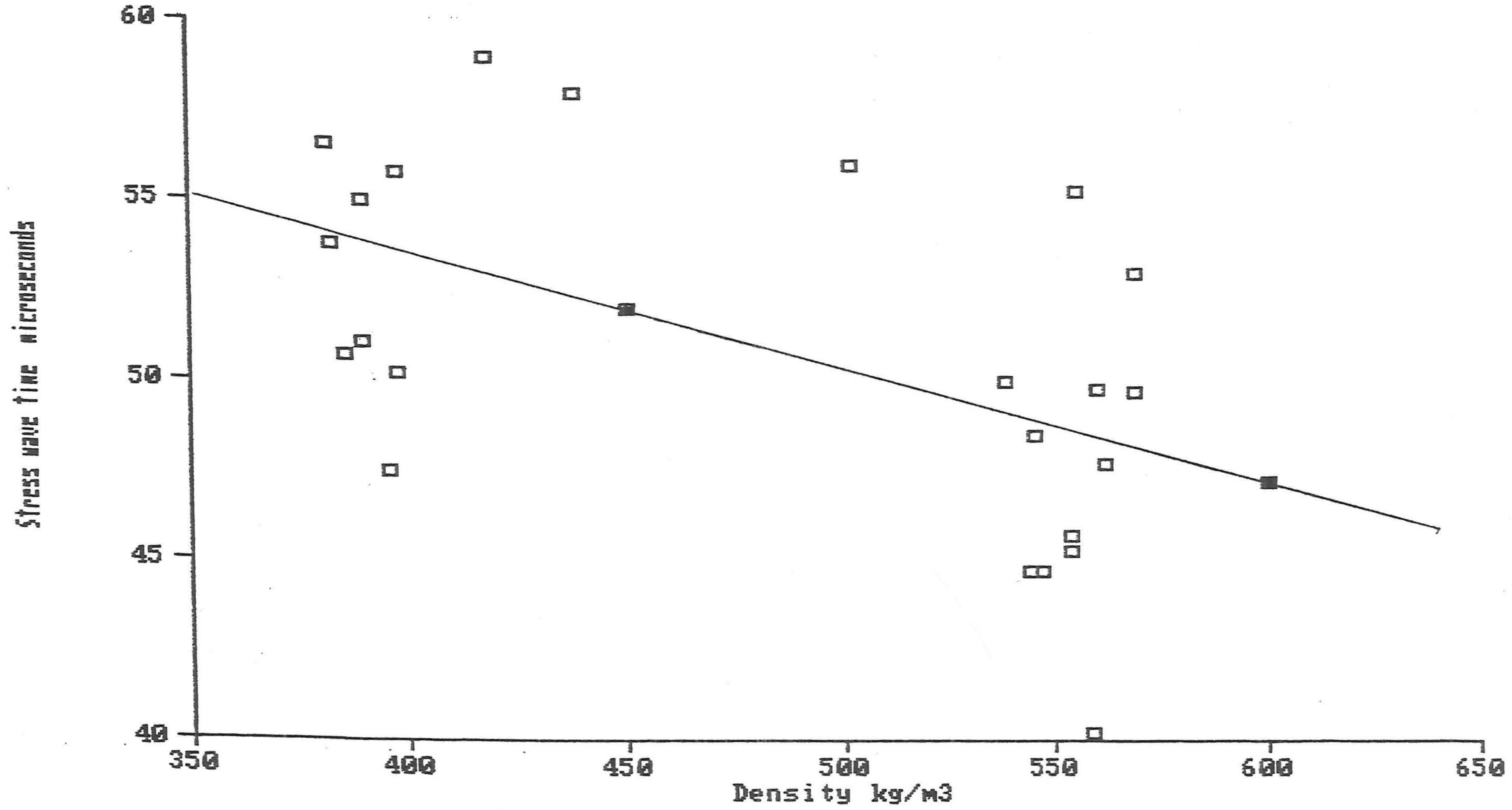
DISTANCE FROM PITH (cm)

Regression Output:

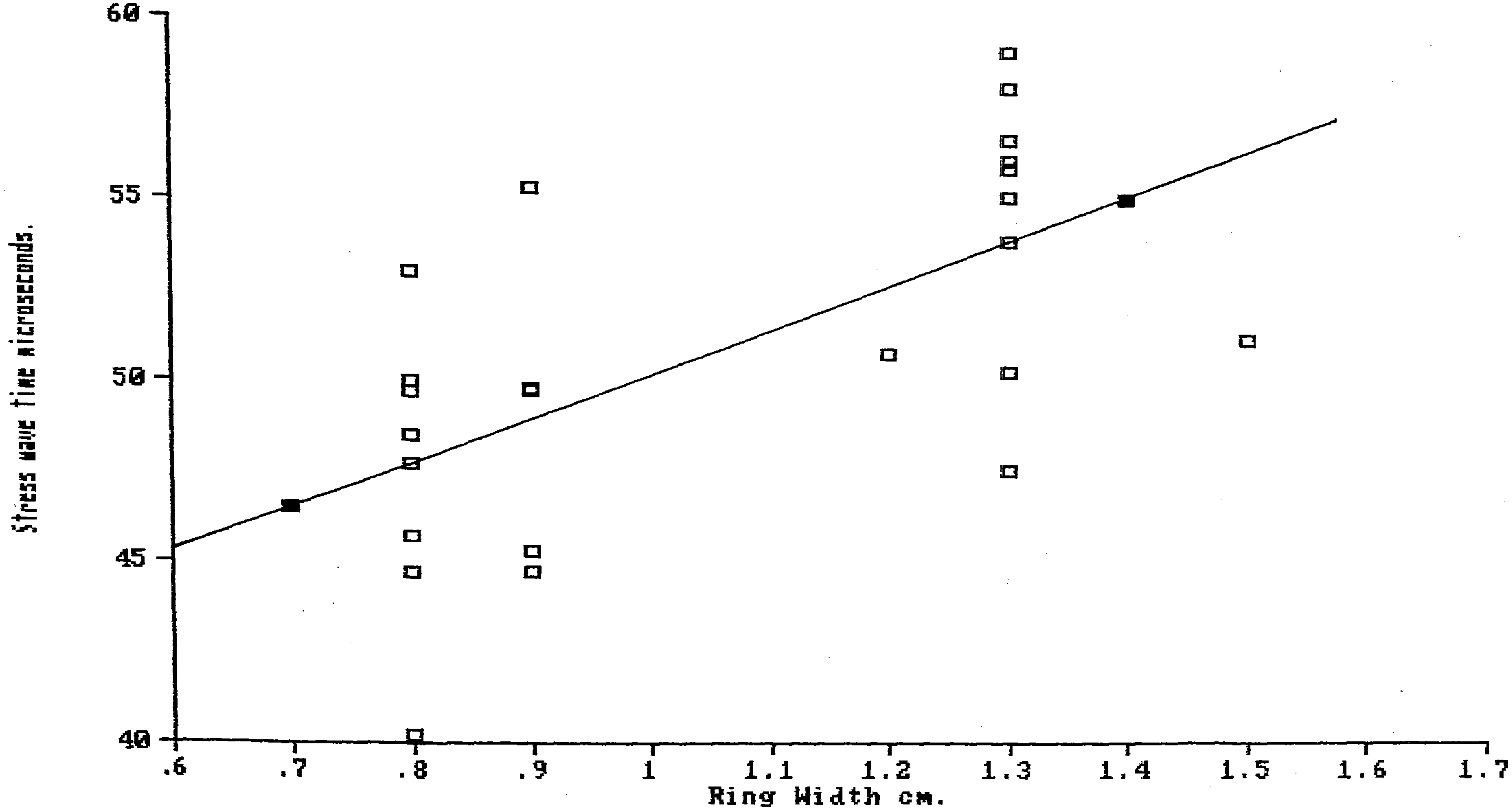
Constant	56.94033
Std Err of Y Est	3.923515
R^2	0.360739
No of Observations	24
Degrees of Freedom	22
X Coefficient(s)	-0.63409
Std Err of Coefficient	0.179963

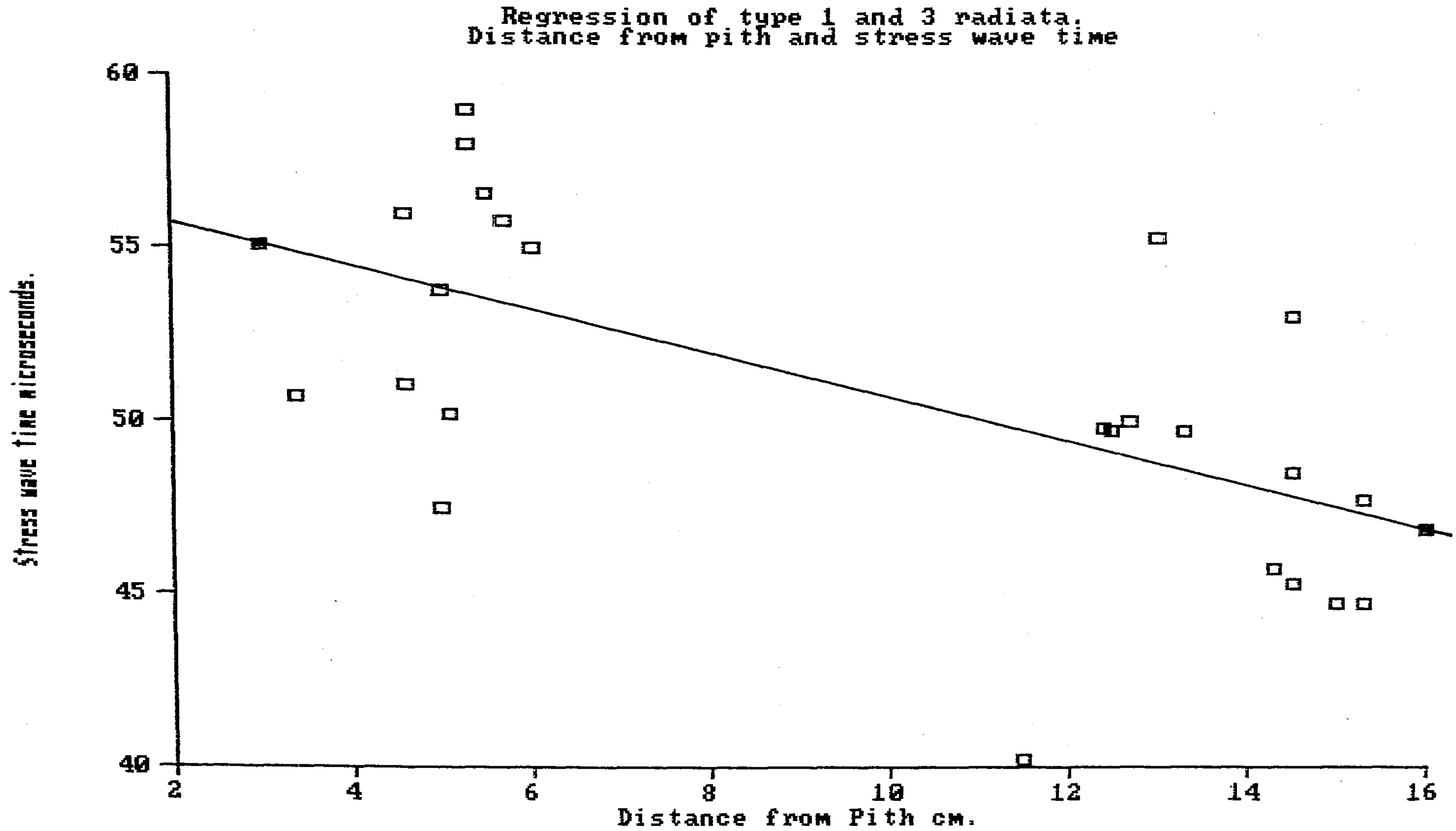
$$Y = -0.63X + 56.94$$

Comparison of type 1 and 3 radiata data
Density and stress wave time.



Regression of type 1 and 3 radiata.
Ring width and stress wave time.




Regression of type 1 and 3 radiata.
Distance from pith and stress wave time
Stress wave time microseconds.
60
55
50
45
40
2
4
6
8
10
12
14
16
Distance from Pith cm.

MULTIPLE REGRESSION ANALYSIS

Stress Wave Time against Density and Ring Width

Regression Output:

Constant		22.51354
Std Err of Y Est		3.890832
R^2		0.399920
No of Observations		24
Degrees of Freedom		21
X Coefficient(s)	0.019328	17.84325
Std Err of Coefficient	0.027134	8.735563

$$Y = 0.02X + 17.84X + 22.51$$

Stress Wave Time against Density and Distance from Pith

Regression Output:

Constant		58.86525
Std Err of Y Est		4.004540
R^2		0.364333
No of Observations		24
Degrees of Freedom		21
X Coefficient(s)	0.009300	-0.78372
Std Err of Coefficient	0.026989	0.471494

$$Y = 0.01X - 0.78X + 53.87$$

CONCLUSION

This study has shown that the Metriguard Model 239A Stress Wave Timer does have a lot of potential as a method for testing wood non-destructively.

There is no doubt that the 239A does predict strength characteristics of wood with accuracy. The stress waves, when passed through the pieces of timber do respond predictably. Propagation times altered depending on the number and type of defects present in the timber.

Compared to a mechanical bending test the stress wave timer over-estimated the modulus of elasticity by only 17.5 percent. This difference is considered to be systematic and therefore the stress wave timer appears to be accurate.

Whether or not the instrument is effective outside the lab however is still in question. The instrument is highly sensitive and had to be used carefully to avoid getting erratic measurements.

It is beyond the scope of this report to offer conclusive evidence as to whether the instrument, in its present stage of development, could be used for accurate, in-place assessment. Available literature tends to indicate that it can be used in this way.

A much larger data base should be used for any further investigation into the way the 239A predicts strength characteristics and defects in wood.

REFERENCES

1. Gerhards, C C, *Longitudinal stress waves for lumber stress grading: factors affecting applications: state of the art.* Forest Products Journal, Vol 32, No 2, 1982.

2. Gerhards, C C, *Effect of cross grain on stress waves in lumber*. Research Paper. FPL-RP-368. Madison, WI: US Department of Agriculture, Forest Service, Forest Products Laboratory, 1981.

3. MANUAL, Metriguard Model 239A Stress Wave Timer. *Care and instruction, theory and date reduction*. Metriguard, Incorporated, PO Box 399, Pullman, Washington (509) 332-7526.

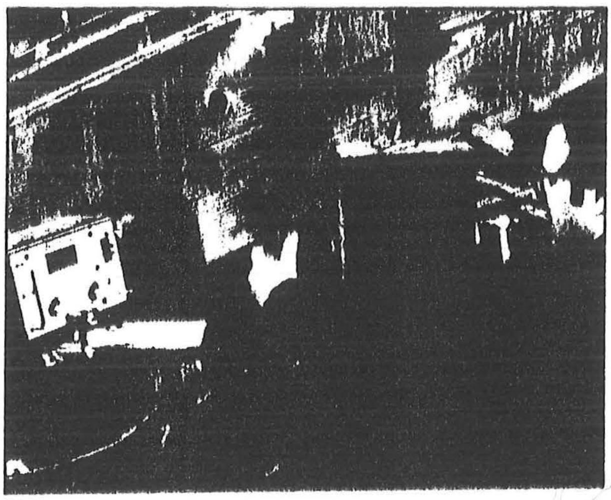
4. Ross, R J & Pellerin, R F, *Nondestructive testing for assessing wood members in structures: a review.* Gen. Tech. Rep. FPL-GTR-70. Madison, WI: US Department of Agriculture, Forest Service, Forest Products Laboratory, 1991.

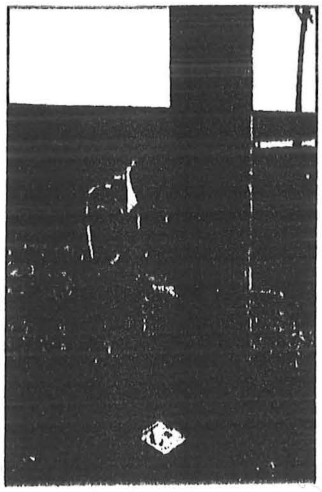
APPENDIX 1

PORTABLE STRESS WAVE TIMER

MATERIAL TESTING with STRESS WAVES

The velocity c at which a mechanical stress wave travels in material is a function of the material's modulus of elasticity E and density ρ, according to the formula $c = (E/\rho)^{0.5}$. Thus, if c is measured and either E or ρ is known, the remaining quantity can be computed. In addition, research has shown that the wave velocity alone can be an excellent indicator of important mechanical properties of wood and wood-based products. Under license from Washington State University Research Foundation, Metriguard Inc. for more than a decade has designed and developed equipment for measuring stress wave velocity. The culmination of this work is the portable Model 239A Stress Wave Timer. In this instrument, unnecessary frills have been eliminated, and important features have been added as a result of field experience and user feedback.





The Metriguard Model 239A Stress Wave Timer is a valuable tool for evaluating wood structural members in place

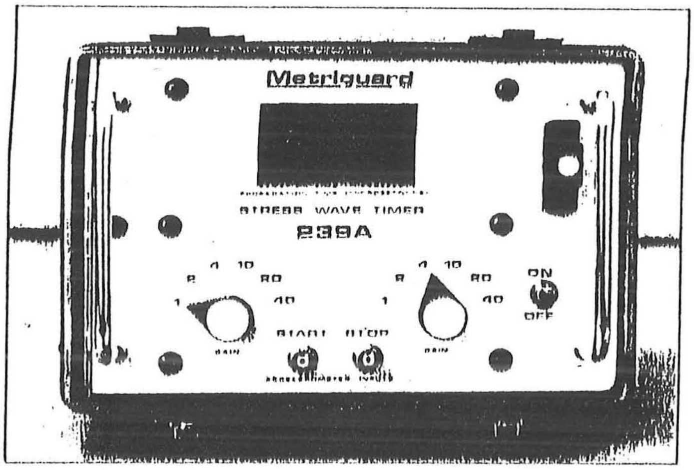
Contact Metriguard, Inc. for additional information on accessories for the 239A. Many kinds of stress wave applicators, detectors, and cables are available. New devices are under development for special applications.

Metriguard Inc.

serving the forest products industry through electronics

P.O. Box 399 TEL: (509) 332-7526
PULLMAN, WA 99163 (509) 332-1600
U.S.A. TELEX: 910 350 6817 (METRIGRD WA)

METRIGUARD Model 239A Portable Stress Wave Timer



HOW THE MODEL 239A WORKS: A mechanical stress wave is induced in the material by a hammer or by other means and is detected with accelerometers at two points along the propagation path. The timer starts when the wave front arrives at the first accelerometer; the timer stops when the wave front arrives at the second accelerometer and displays the propagation time between accelerometers in microseconds.

[ ] Digital readout gives instant indication of a material's quality

[ ] Nondestructive evaluation of material properties.

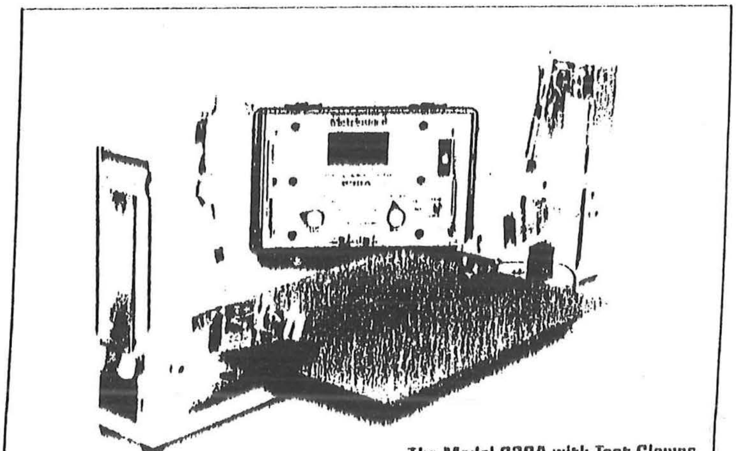
[ ] Test material in place while in use.

[ ] Portable; Rugged; Accurate; Repeatable; Low in cost.

[ ] Reliable; Field Proven; One year warranty.

[ ] Easy to use; Special options available.

[ ] Standard components for long term maintainability.



The Model 239A with Test Clamps

TYPICAL APPLICATIONS

- Detect decay in bridge, stadium, and mine timbers, waterfront structures, laminated beams, and utility poles
- Measure anisotropy (particle orientation) in paper, panel products, and composites
- Laboratory quality control programs
- Production line quality control
- Quality assurance programs for composite materials
- Sorting or grading according to material properties
- Quality control of incoming shipments
- Find decay in standing timber

SPECIFICATIONS

Power Requirements: Nine volt battery (Eveready #522 alkaline cell or equivalent). A built in regulator gives a low battery indication when the voltage drops below the value required for the regulator to function. Battery life in excess of 40 hours.

Resolution: ± 1 microsecond.

Controls: Individual front panel sensitivity switches and internal level controls for the "start" and "stop" channels.

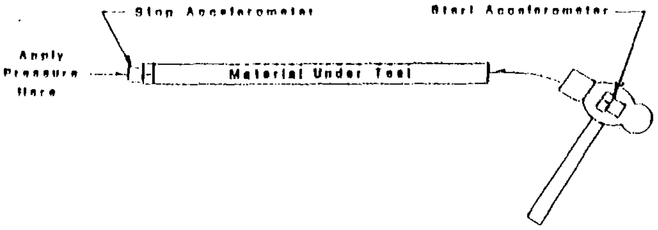
Accelerometers: Ten-foot shielded cables with microdot connectors.

Portability: Remote operation without auxiliary power. Rugged carrying cases.

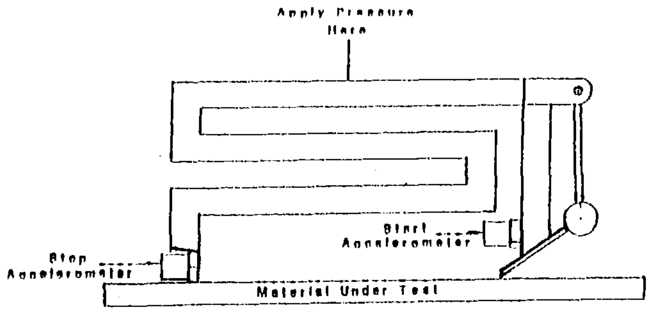
Weight: 20 lb., including clamps

Dimensions: Instrument case — 7"x9"x9" high
Clamp carrying case — 8"x11"x11" high

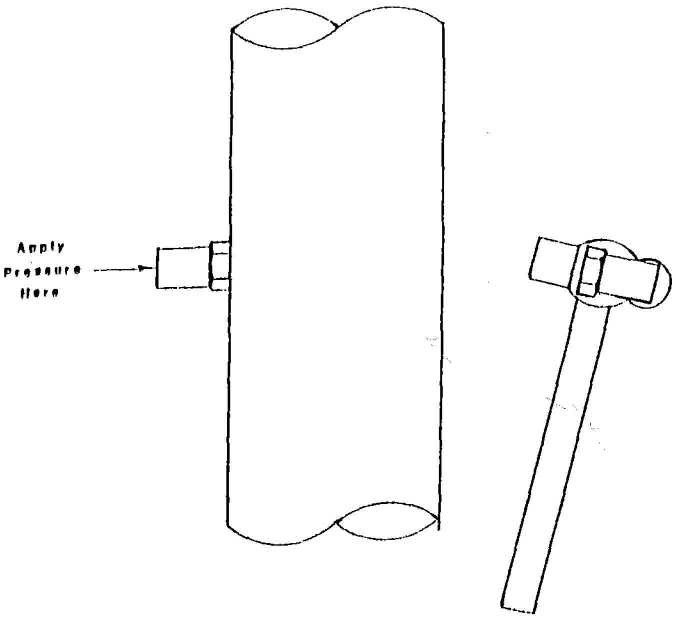
APPENDIX 2



Impactor mounting of the START accelerometer. In this arrangement, the accelerometer is mounted to the impactor so its base is pointed toward the point of impact. When the stress wave travels through the impactor, it arrives at the accelerometer base first.



Side view of the Metriguard Model 239A-TC fixture used to measure stress wave times over a fixed distance. The frame shape assures that the stress wave passes through the material under test before it gets through the clamp fixture. The fixture is hand held and contains a pendulum impactor. It is easily picked up and rotated 90° for measurement of propagation time in a direction orthogonal to the first measurement.



Stress wave time measurement technique for decay detection in a structural member such as a utility pole. Note the orientation of the START and STOP accelerometers. Decayed members will typically result in a large increase in measured stress wave time.

APPENDIX 3

Data recorded for the calculation of the zero offset correction factor.

Species tested = Douglas Fir, 2.0 m lengths of 100 x 50 mm. Clear wood.
Stress wave times have been measured in microseconds.

Piece 1 Density = 643 kg/m^3

Amplifier Gain = 1

TEST #	TEST DISTANCE (cm)									
	17.9	38.1	58.4	78.8	99.1	119.4	139.6	159.8	180.3	207.0
1	32	76	99	147	178	217	252	280	331	384
2	39	79	93	143	172	210	250	281	327	399
3	36	74	97	151	171	209	258	283	328	394
4	32	79	90	158	179	206	252	278	328	397
5	37	69	99	150	179	206	251	276	331	393
6	36	80	92	138	174	211	242	272	338	392
Mean	35.3	76.2	95.0	147.8	175.5	209.8	250.8	278.3	330.5	393.2

Amplifier Gain = 2

TEST #	TEST DISTANCE (cm)									
	17.9	38.1	58.4	78.8	99.1	119.4	139.6	159.8	180.3	207.0
1	29	73	99	155	173	217	255	285	338	380
2	31	71	106	151	180	214	257	275	327	384
3	39	76	106	158	176	217	257	275	325	384
4	36	68	96	150	180	211	251	278	329	390
5	34	77	98	162	177	212	254	271	330	384
6	31	82	99	153	178	204	255	277	329	378
Mean	33.3	74.5	100.7	154.8	177.3	212.5	254.8	276.8	329.7	383.3

Amplifier Gain = 4

TEST #	TEST DISTANCE (cm)									
	17.9	38.1	58.4	78.8	99.1	119.4	139.6	159.8	180.3	207.0
1	31	75	100	153	182	209	258	282	331	379
2	31	79	100	153	177	212	251	277	328	380
3	43	79	105	147	174	209	254	278	327	376
4	36	72	101	154	178	216	257	279	329	380
5	34	80	103	151	169	210	252	281	331	378
6	33	78	105	153	174	209	252	275	326	381
Mean	34.7	77.2	102.3	151.8	175.7	210.8	254.0	278.7	328.7	379.0

(Offset Correction Data continued ...)

Amplifier Gain = 10

TEST #	TEST DISTANCE (cm)									
	17.9	38.1	58.4	78.8	99.1	119.4	139.4	159.8	180.3	207.0
1	31	73	105	148	171	209	258	283	331	378
2	41	80	102	146	176	209	257	281	328	377
3	41	80	102	147	172	207	258	279	323	376
4	30	75	105	145	183	218	255	283	331	377
5	35	78	105	145	176	214	253	276	327	379
6	40	80	108	142	173	214	252	280	326	377
Mean	36.3	77.7	104.5	145.5	175.2	211.8	255.5	280.3	327.7	377.3

Amplifier Gain = 20

TEST #	TEST DISTANCE (cm)									
	17.9	38.1	58.4	78.8	99.1	119.4	139.6	159.8	180.3	207.0
1	29	72	108	142	184	214	259	284	330	377
2	31	81	103	145	181	210	255	273	324	376
3	35	80	98	142	181	208	257	275	322	373
4	35	81	109	144	182	218	251	284	320	372
5	40	82	104	140	177	210	252	280	329	372
6	41	77	105	145	179	210	253	278	323	374
Mean	35.2	78.8	104.5	143.0	180.7	211.7	254.5	279.0	324.7	374.0

Amplifier Gain = 40

TEST #	TEST DISTANCE (cm)									
	17.9	38.1	58.4	78.8	99.1	119.4	139.6	159.8	180.3	207.0
1	37	80	101	144	182	209	256	281	330	374
2	34	77	108	141	181	212	253	281	328	373
3	43	84	105	144	182	204	253	281	323	379
4	30	83	107	144	169	208	256	288	329	378
5	42	83	107	145	180	206	250	281	325	375
6	45	84	108	149	179	208	249	279	327	376
Mean	38.5	81.8	106.0	144.5	178.8	207.8	252.8	281.8	327.0	375.8

Data recorded for the calculation of the zero offset correction factor.

Species tested = Douglas Fir, 2.0 m lengths of 100 x 50 mm.
Clear wood.
Stress wave times have been measured in microseconds.

Piece 2 Density = 677 kg/m^3

Amplifier Gain = 1

TEST #	TEST DISTANCE (cm)									
	17.0	37.3	57.8	77.9	98.5	118.7	139.3	159.9	180.1	200.7
1	34	76	86	132	148	195	231	274	304	381
2	29	85	95	131	153	202	232	280	305	379
3	36	80	98	133	150	197	239	282	306	376
4	44	72	80	134	165	191	232	281	296	382
5	25	73	86	134	168	189	236	278	309	382
6	35	79	93	128	160	198	238	278	298	381
Mean	33.8	77.5	89.7	132.0	157.3	195.3	234.7	278.8	303.0	380.2

Amplifier Gain = 2

TEST #	TEST DISTANCE (cm)									
	17.0	37.3	57.8	77.9	98.5	118.7	139.3	159.9	180.1	200.7
1	29	86	96	135	164	204	237	283	311	374
2	30	82	94	135	162	199	240	279	392	379
3	26	78	92	132	172	204	238	271	302	378
4	39	83	96	129	168	206	246	283	312	377
5	30	81	97	126	173	199	251	273	305	373
6	29	86	102	137	176	201	245	273	309	380
Mean	30.5	82.7	96.2	132.3	169.2	202.2	242.8	277.0	321.8	376.8

Amplifier Gain = 4

TEST #	TEST DISTANCE (cm)									
	17.0	37.3	57.8	77.9	98.5	118.7	139.3	159.9	180.1	200.7
1	30	83	92	133	175	205	238	275	310	371
2	35	79	95	131	173	207	249	279	313	372
3	36	84	96	135	178	200	246	278	313	373
4	39	84	95	125	181	208	247	285	303	373
5	44	83	98	126	178	207	245	280	313	370
6	41	94	108	133	172	207	243	280	312	369
Mean	37.5	84.5	97.3	130.5	176.2	205.7	244.7	279.5	310.7	371.3

(Offset Correction Data continued ...)

Amplifier Gain = 10

TEST #	TEST DISTANCE (cm)									
	17.0	37.3	57.8	77.9	98.5	118.7	139.3	159.9	180.1	200.7
1	45	84	105	124	176	210	242	280	298	371
2	48	84	99	133	177	207	244	280	303	372
3	46	83	103	131	177	197	243	285	305	373
4	35	80	94	126	179	203	245	282	304	373
5	34	81	93	138	175	201	241	282	309	370
6	41	83	104	134	178	208	244	282	310	369
Mean	41.5	82.5	99.7	131.0	177.0	204.3	243.2	281.8	304.8	371.3

Amplifier Gain = 20

TEST #	TEST DISTANCE (cm)									
	17.0	37.3	57.8	77.9	98.5	118.7	139.3	159.9	180.1	200.7
1	33	84	90	132	176	199	236	277	309	370
2	32	83	102	124	180	203	236	279	310	369
3	36	83	104	129	177	208	243	280	297	370
4	37	89	95	142	175	204	242	284	305	368
5	37	88	102	138	177	201	242	282	311	368
6	41	83	99	134	178	208	234	282	311	373
Mean	36.0	85.0	98.7	133.2	177.2	203.8	238.8	280.7	307.2	369.7

Amplifier Gain = 40

TEST #	TEST DISTANCE (cm)									
	17.0	37.3	57.8	77.9	98.5	118.7	139.3	159.9	180.1	200.7
1	37	81	96	138	179	207	242	283	311	369
2	39	79	101	133	175	204	245	284	310	374
3	40	81	106	135	179	207	242	285	310	368
4	36	78	96	133	183	207	237	284	306	374
5	43	81	103	127	182	206	247	281	310	367
6	46	83	105	135	179	209	244	284	305	368
Mean	40.2	80.5	101.2	133.5	179.5	206.7	242.8	283.5	308.7	370.0

Data recorded for the calculation of the zero offset correction factor.

Species tested = Douglas Fir, 2.0 m lengths of 100 x 50 mm.
Clear wood.
Stress wave times have been measured in microseconds.

Piece 3 Density = 673 kg/m^3

Amplifier Gain = 1

TEST #	TEST DISTANCE (cm)									
	17.6	37.9	58.3	78.5	98.8	119.2	139.6	159.8	180.4	200.7
1	29	89	93	133	142	196	242	274	287	382
2	35	96	87	124	152	198	252	280	287	385
3	28	96	92	124	151	190	247	274	288	388
4	26	92	83	122	154	191	239	274	289	388
5	35	85	82	126	159	192	251	270	283	386
6	21	100	87	125	154	196	247	276	289	388
Mean	29.0	93.0	87.3	125.7	152.0	193.8	246.3	274.7	287.2	386.2

Amplifier Gain = 2

TEST #	TEST DISTANCE (cm)									
	17.6	37.9	58.3	78.5	98.8	119.2	139.6	159.8	180.4	200.7
1	35	99	86	135	179	206	253	277	306	384
2	32	103	87	139	182	196	252	272	312	383
3	31	100	98	137	187	199	253	283	300	383
4	29	98	89	132	177	206	249	279	305	382
5	25	92	92	134	178	202	251	284	296	384
6	39	98	90	136	187	191	249	281	306	386
Mean	31.8	98.3	90.3	135.5	181.7	200.0	251.2	279.3	304.2	383.7

Amplifier Gain = 4

TEST #	TEST DISTANCE (cm)									
	17.6	37.9	58.3	78.5	98.8	119.2	139.6	159.8	180.4	200.7
1	28	96	89	138	181	192	258	286	308	383
2	37	91	95	135	180	204	256	283	312	388
3	34	88	89	141	183	202	257	285	311	382
4	30	91	93	139	175	196	246	281	304	378
5	36	90	82	137	185	198	257	279	314	381
6	35	89	97	135	181	192	246	280	310	381
Mean	33.3	90.8	90.8	137.5	180.8	197.3	253.3	282.3	309.8	382.2

(Offset Correction Data continued ...)

Amplifier Gain = 10

TEST #	TEST DISTANCE (cm)									
	17.6	37.9	58.3	78.5	98.8	119.2	139.6	159.8	180.4	200.7
1	29	87	96	138	176	204	253	279	311	374
2	32	82	90	141	177	209	255	281	313	379
3	34	86	92	138	173	202	256	276	308	376
4	37	96	85	138	173	206	243	277	309	379
5	35	89	96	131	177	202	255	281	308	376
6	32	90	90	131	171	212	252	280	306	376
Mean	33.2	88.3	91.5	136.2	174.5	205.8	252.3	279.0	309.2	376.7

Amplifier Gain = 20

TEST #	TEST DISTANCE (cm)									
	17.6	37.9	58.3	78.5	98.8	119.2	139.6	159.8	180.4	200.7
1	35	84	98	141	178	209	249	272	308	372
2	41	86	100	137	175	204	253	278	305	377
3	39	87	101	138	179	211	250	268	311	376
4	37	86	100	147	179	212	254	275	304	376
5	35	87	98	138	175	214	253	277	310	375
6	40	83	97	146	177	212	252	280	301	363
Mean	37.8	85.5	99.0	141.2	177.2	210.3	251.8	275.0	306.5	373.2

Amplifier Gain = 40

TEST #	TEST DISTANCE (cm)									
	17.6	37.9	58.3	78.5	98.8	119.2	139.6	159.8	180.4	200.7
1	35	81	91	145	176	209	252	275	330	371
2	37	81	88	147	176	212	252	277	295	371
3	40	88	93	143	176	201	249	285	301	373
4	35	98	95	142	177	195	247	276	311	372
5	41	88	90	139	179	199	250	283	310	370
6	47	91	97	145	174	202	251	284	308	369
Mean	39.2	87.8	92.3	143.5	176.3	203.0	250.2	280.0	309.2	371.0

APPENDIX 3

Regression Analysis of Piece 1

Summary of Means for Data

Distance (cm)	AMPLIFIER GAIN					
	1	2	4	10	20	40
17.9	35.3	33.3	34.7	36.3	35.2	38.5
38.1	76.2	74.5	77.2	77.7	78.8	81.8
58.4	95.0	100.7	102.3	104.5	104.5	106.0
78.8	147.8	154.8	151.8	145.5	143.0	144.5
99.1	175.5	177.3	175.7	175.2	180.7	178.8
119.4	209.8	212.5	210.8	211.8	211.7	207.8
139.6	250.8	254.8	254.0	255.5	254.5	252.8
159.8	278.3	276.8	278.7	280.3	279.0	281.8
180.3	330.5	329.7	328.7	327.7	324.7	327.0
207.0	393.2	383.3	379.0	377.3	374.0	375.8

Regression Output: (GAIN = 1)

Constant	-3.12851
Std Err of Y Est	9.394461
R^2	0.994114
No of Observations	10
Degrees of Freedom	8

X Coefficient(s)	1.840572
Std Err of Coef	0.050071

Regression Output: (GAIN = 2)

Constant	1.259436
Std Err of Y Est	7.562497
R^2	0.996036
No of Observations	10
Degrees of Freedom	8

X Coefficient(s)	1.807270
Std Err of Coef	0.040306

(Regression Analysis continued ...)

Regression Output: (GAIN = 4)

Constant	3.050353
Std Err of Y Est	6.384817
R^2	0.997105
No of Observations	10
Degrees of Freedom	8
X Coefficient(s)	1.786595
Std Err of Coef	0.034030

Regression Output: (GAIN = 10)

Constant	3.554157
Std Err of Y Est	5.036848
R^2	0.998185
No of Observations	10
Degrees of Freedom	8
X Coefficient(s)	1.781007
Std Err of Coef	0.026845

Regression Output: (GAIN = 20)

Constant	4.815505
Std Err of Y Est	4.541073
R^2	0.998496
No of Observations	10
Degrees of Freedom	8
X Coefficient(s)	1.764334
Std Err of Coef	0.024203

Regression Output: (GAIN = 40)

Constant	6.412456
Std Err of Y Est	5.378639
R^2	0.997876
No of Observations	10
Degrees of Freedom	8
X Coefficient(s)	1.757716
Std Err of Coef	0.028667

Regression Analysis of Piece 2

Summary of Means for Data

Distance (cm)	AMPLIFIER GAIN					
	1	2	4	10	20	40
17.0	33.8	30.5	37.5	41.5	36.0	40.2
37.3	77.5	82.7	84.5	82.5	85.0	80.5
57.8	89.7	96.2	97.3	99.7	98.7	101.2
77.9	132.0	132.3	130.5	131.0	133.2	133.5
98.5	157.3	169.2	176.2	177.0	177.2	179.5
118.7	195.3	202.2	205.7	204.3	203.8	206.7
139.3	234.7	242.8	244.7	243.2	238.8	242.8
159.9	278.8	277.0	279.5	281.8	280.7	283.5
180.1	303.0	321.8	310.7	304.8	307.2	308.7
200.7	380.2	376.8	371.3	371.3	369.7	370.0

Regression Output: (GAIN = 1)

Constant	-5.09172
Std Err of Y Est	14.57745
R^2	0.984597
No of Observations	10
Degrees of Freedom	8

X Coefficient(s)	1.778161
Std Err of Coef	0.078630

Regression Output: (GAIN = 2)

Constant	-2.45903
Std Err of Y Est	10.75689
R^2	0.991748
No of Observations	10
Degrees of Freedom	8

X Coefficient(s)	1.799200
Std Err of Coef	0.058022

(Regression Analysis continued ...)

Regression Output: (GAIN = 4)

Constant	4.254015
Std Err of Y Est	9.968743
R^2	0.992446
No of Observations	10
Degrees of Freedom	8

X Coefficient(s)	1.743340
Std Err of Coef	0.053771

Regression Output: (GAIN = 10)

Constant	6.492981
Std Err of Y Est	10.41195
R^2	0.991562
No of Observations	10
Degrees of Freedom	8

X Coefficient(s)	1.722010
Std Err of Coef	0.056161

Regression Output: (GAIN = 20)

Constant	5.385042
Std Err of Y Est	10.10211
R^2	0.992089
No of Observations	10
Degrees of Freedom	8

X Coefficient(s)	1.725946
Std Err of Coef	0.054490

Regression Output: (GAIN = 40)

Constant	6.345495
Std Err of Y Est	8.695197
R^2	0.994167
No of Observations	10
Degrees of Freedom	8

X Coefficient(s)	1.731921
Std Err of Coef	0.046901

Regression Analysis of Piece 3

Summary of Means for Data

Distance (cm)	AMPLIFIER GAIN					
	1	2	4	10	20	40
17.6	29.0	31.8	33.3	33.2	37.8	39.2
37.9	93.0	98.3	90.8	88.3	85.5	87.8
58.3	87.3	90.3	90.8	91.5	99.0	92.3
78.5	125.7	135.5	137.5	136.2	141.2	143.5
98.8	152.0	181.7	180.8	174.5	177.2	176.3
119.2	193.8	200.0	197.3	205.8	210.3	203.0
139.6	246.3	251.2	253.3	252.3	251.8	250.2
159.8	274.7	279.3	282.3	279.0	275.0	280.0
180.4	287.2	304.2	309.8	309.2	306.5	309.2
200.7	386.2	383.7	382.2	376.7	373.2	371.0

Regression Output: **(GAIN = 1)**

Constant	-4.70399
Std Err of Y Est	21.41583
R^2	0.966551
No of Observations	10
Degrees of Freedom	8
X Coefficient(s)	1.762229
Std Err of Coef	0.115902

Regression Output: **(GAIN = 2)**

Constant	3.253784
Std Err of Y Est	17.03846
R^2	0.978591
No of Observations	10
Degrees of Freedom	8
X Coefficient(s)	1.763349
Std Err of Coef	0.092211

(Regression Analysis continued ...)

Regression Output: (GAIN = 4)

Constant	1.002992
Std Err of Y Est	14.65258
R^2	0.984471
No of Observations	10
Degrees of Freedom	8
X Coefficient(s)	1.785909
Std Err of Coef	0.079299

Regression Output: (GAIN = 10)

Constant	4.35897
Std Err of Y Est	12.26844
R^2	0.988919
No of Observations	10
Degrees of Freedom	8
X Coefficient(s)	1.774120
Std Err of Coef	0.066396

Regression Output: (GAIN = 20)

Constant	6.921798
Std Err of Y Est	10.36135
R^2	0.991675
No of Observations	10
Degrees of Freedom	8
X Coefficient(s)	1.731098
Std Err of Coef	0.056075

Regression Output: (GAIN = 40)

Constant	6.072754
Std Err of Y Est	11.04800
R^2	0.990580
No of Observations	10
Degrees of Freedom	8
X Coefficient(s)	1.734298
Std Err of Coef	0.059791

APPENDIX 5

TROMBONE MEASUREMENTS

Douglas fir : Pieces 1 - 3

Piece 1

NUM	AMPLIFIER GAIN								
	10a	10b	10c	20a	20b	20c	40a	40b	40c
1	65	59	54	60	57	56	58	59	55
2	71	59	55	61	58	55	55	58	54
3	59	58	57	59	58	56	57	57	54
4	58	62	58	63	57	55	57	58	52
5	62	63	58	62	58	55	56	58	55
6	60	60	57	75	57	56	60	58	55
7	58	60	58	57	58	54	59	59	57
8	57	60	59	56	59	55	57	57	57
9	57	62	59	56	58	56	58	57	60
10	58	61	61	60	59	54	59	55	60
Mean	60.5	60.4	57.6	60.9	57.9	55.2	57.6	57.6	55.9

Piece 2

NUM	AMPLIFIER GAIN								
	10a	10b	10c	20a	20b	20c	40a	40b	40c
1	59	56	57	56	55	56	57	52	60
2	59	59	57	56	57	57	58	51	54
3	60	55	61	57	54	61	59	52	55
4	59	57	59	57	52	59	58	54	57
5	58	56	56	57	52	62	59	53	55
6	57	57	55	56	53	57	58	54	59
7	60	56	58	57	54	56	58	54	55
8	60	55	55	55	54	58	57	54	56
9	61	57	57	58	53	56	57	54	57
10	60	56	56	57	55	59	56	54	57
Mean	59.3	56.4	57.8	56.6	53.9	58.1	57.7	53.2	56.5

(Trombone Measurements continued ...)

Piece 3

NUM	AMPLIFIER GAIN								
	10a	10b	10c	20a	20b	20c	40a	40b	40c
1	59	60	61	56	56	60	58	59	60
2	59	58	61	57	60	61	59	61	60
3	59	57	61	58	63	62	59	61	61
4	62	61	60	57	61	62	58	59	60
5	61	61	61	60	60	60	59	57	59
6	63	62	62	59	62	61	57	59	58
7	61	62	66	59	64	64	58	57	60
8	65	59	64	59	60	60	59	59	61
9	66	58	65	61	64	61	61	61	62
10	65	61	62	59	64	60	57	58	62
Mean	62.0	59.9	62.3	58.5	61.4	61.1	58.5	59.1	60.3

Times measured in microseconds.

APPENDIX 6

Stress wave timer data for 4 types of radiata

Type 1 = Clear radiata with pith.

Stress wave times are in microseconds.
Radiata is in 20 cm lengths of 100 x 50 mm.
Data is not yet corrected for offset.
Gain setting = 40.

NUMBER	PIECE					
	A	B	C	D	E	F
1	61	62	46	60	56	51
2	57	58	43	61	53	51
3	60	64	58	61	53	62
4	63	68	57	64	60	63
5	62	67	58	64	59	61
6	65	67	61	64	58	54
Mean	61.3	64.3	53.8	62.3	56.5	57.0
Density kg/m³	390	438	396	501	398	386

Type 2 = Knotty radiata with pith.

NUMBER	PIECE		
	A	B	C
1	64	66	66
2	67	68	65
3	63	59	68
4	67	67	64
5	61	67	64
6	59	65	69
Mean	63.5	65.3	66.0
Density kg/m³	497	528	493

(Stress Wave Timer Data continued ...)

Type 3 = Clear radiata with no pith

NUMBER	PIECE								
	A	B	C	D	E	F	G	H	I
1	42	45	54	45	48	49	45	49	51
2	42	46	58	51	51	47	45	50	49
3	45	48	58	50	50	50	41	54	46
4	47	48	53	52	53	52	42	55	52
5	47	48	53	48	49	47	48	54	46
6	45	51	56	52	49	53	47	56	47
Mean	44.7	47.7	55.3	49.7	50.0	49.7	44.7	53.0	48.5
Density kg/m^3	547	562	555	569	538	569	544	569	545

NUMBER	PIECE								
	J	K	L	M	N	O	P	Q	R
1	46	57	42	45	46	49	56	56	60
2	48	58	42	44	42	51	56	55	64
3	42	60	42	53	46	51	56	49	58
4	48	58	38	58	49	52	60	54	51
5	45	60	37	46	45	55	57	60	49
6	45	61	40	53	44	49	55	49	53
Mean	45.7	59.0	40.2	49.8	45.3	51.1	56.6	53.8	55.8
Density kg/m^3	554	418	559	560	554	390	382	383	398

(Stress Wave Timer Data continued ...)

Type 4 = Knotty radiata with no pitch

NUMBER	PIECE				
	A	B	C	D	E
1	59	78	63	68	61
2	61	78	62	60	58
3	63	75	59	62	59
4	61	73	69	61	65
5	63	71	66	59	59
6	62	73	67	70	60
Mean	61.5	74.6	64.3	63.3	60.3
Density kg/m^3	579	546	661	416	443

APPENDIX 7

Radiata Type 1 - 4 ring width and ring distance from pith measurements

MEASUREMENTS OF BLOCKS - 20 cm length of 100 x 50 mm

	MEASUREMENTS (cm)							
	Type 1		Type 2		Type 3		Type 4	
	Width	Dist	Width	Dist	Width	Dist	Width	Dist
A	1.3	6.0	1.3	5.9	0.8	15.0	0.8	9.3
B	1.3	5.3	1.3	4.5	0.8	15.3	1.2	4.4
C	1.3	5.0	1.3	5.0	0.9	13.0	0.9	14.0
D	1.3	4.6			0.8	13.3	1.3	5.7
E	1.3	5.1			0.8	12.7	1.3	7.2
F	1.2	3.4			0.9	12.5		
G					0.9	15.3		
H					0.8	14.5		
I					0.8	14.5		
J					0.8	14.3		
K					1.3	5.6		
L					0.8	11.5		
M					0.9	12.5		
N					0.9	14.5		
O					1.5	4.6		
P					1.3	5.5		
Q					1.3	5.0		
R					1.3	5.7		
Mean	1.3	4.9	1.3	4.8	1.0	11.4	1.1	8.1

NOTES:

Measurements of ring width are the mean of 4 ring widths taken from each block - measured perpendicular to ring direction.

Measurements of distance from pith were estimated by drawing circles on a sheet of plastic at 5 mm intervals and matching these up with the rings on the blocks of radiata.

The distance from the pith was estimated to a point mid-way through each block.